

# Weak localization of electromagnetic waves and opposition phenomena exhibited by high-albedo atmosphereless solar system objects

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The totality of new and previous optical observations of a class of high-albedo solar system objects at small phase angles reveals a unique combination of extremely narrow brightness and polarization features centered at exactly the opposition. The specific morphological parameters of these features provide an almost unequivocal evidence that they are caused by the renowned effect of coherent backscattering. © 2006 Optical Society of America

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## 1. Introduction

The spectacular effect of coherent backscattering (CB) (or weak localization) of electromagnetic waves by discrete random media was predicted in Ref. 1 and has been the subject of active theoretical and laboratory research for the past two decades (see Refs. 2–7 and references therein). The origin of CB is illustrated in Fig. 1, which shows a layer of discrete random medium illuminated by a plane wave incident in the direction  $\hat{n}_{\text{ill}}$ . If the observation direction  $\hat{n}_{\text{obs}}$  is far from the exact backscattering direction given by  $-\hat{n}_{\text{ill}}$ , then the average effect of interference of conjugate scattered waves going through a group of particles in opposite directions is zero, owing to randomness of particle positions. Consequently, the observer measures some average, incoherent intensity. However, at exactly the opposition ( $\hat{n}_{\text{obs}} = -\hat{n}_{\text{ill}}$ ), the phase difference between the conjugate paths involving any configuration of particles is identically equal to zero, and the interference is always constructive.

Among the most salient manifestations of CB are the brightness opposition effect (BOE) and the so-called polarization opposition effect (POE).<sup>8</sup> The former is observed in the form of a narrow intensity peak centered at exactly the backscattering direction. The latter is observed, with unpolarized incident light, in the form of a sharp asymmetric negative-polarization feature with a minimum at a very small phase angle (the angle between the unit vectors  $-\hat{n}_{\text{ill}}$  and  $\hat{n}_{\text{obs}}$ ).<sup>9</sup> Both effects are clearly seen in Fig. 2, which depicts the results of theoretical computations of the normalized intensity and the degree of linear polarization of light reflected by a half-space of nonabsorbing Rayleigh particles illuminated by an unpolarized parallel beam incident normally to the boundary of the scattering medium.<sup>12</sup>

Both BOE and POE have been observed in numerous controlled laboratory experiments. However, the subtlety of these effects, the complexity and incompleteness of the corresponding theory, and the extremely infrequent occurrence of suitable scattering configurations may seem to make essentially improbable a direct and definitive detection of CB in astronomical observations of celestial objects. However, as this paper will report, there is an almost unequivocal evidence that CB is present in precise, long-term photometric and polarimetric observations of sunlight reflected by high-albedo atmosphereless solar system bodies (ASSBs) covered with fine-grained so-called regolith surfaces.

## 2. Observations and Discussion

It had been hypothesized early on<sup>13,14</sup> that CB might play a role in forming the renowned photometric op-

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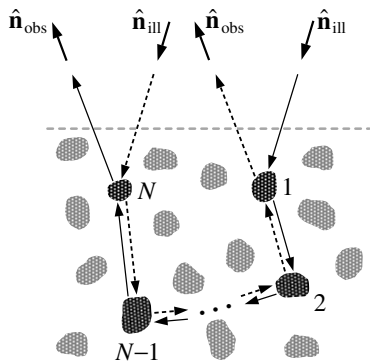


Fig. 1. Schematic explanation of CB. The direct (solid arrows) and reverse (dashed arrows) wave paths go through the same group of  $N$  particles, but in opposite directions.

position effect exhibited by most ASSBs, including the Moon. However, the same effect can be produced by other optical mechanisms such as shadow hiding.<sup>15</sup> Therefore, it was suggested in Ref. 8 that a reliable detection of CB for an ASSB requires the observation of more than one manifestation of CB and a verification that the observations do not contradict theoretical predictions of the plausible ranges of measured parameters. These theoretical predictions can be summarized as follows.

1. By virtue of being the result of multiple scattering, CB is more likely to be observed for high-albedo ASSBs rather than for low-albedo objects such as the Moon.
2. Irrespective of particle size relative to the wavelength, CB causes BOE as a narrow intensity peak centered at exactly the opposition. The observed angular width and amplitude of this peak must be in reasonable agreement with the results of theoretical computations of CB for the expected range of particle sizes, refractive indices, and packing densities (e.g., Refs. 7 and 16–18).

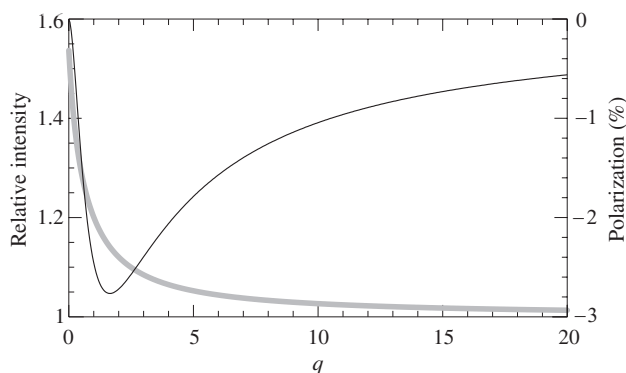


Fig. 2. Angular profiles of BOE (thick gray curve) and POE (thin black curve). The reflected intensity is divided by that of the incoherent background. The degree of linear polarization is defined as the Stokes-parameter ratio  $-Q/I$  with the meridional plane of the reflection direction serving as the reference plane.<sup>11</sup> The dimensionless angular parameter  $q$  is defined as the product of the phase angle, the wavenumber, and the mean free path of light in the scattering medium.

3. Since the incident sunlight is essentially unpolarized, BOE must be accompanied by POE provided that a significant fraction of the regolith surface is composed of wavelength-sized or smaller grains.<sup>8,10,12,19,20</sup> The angular width of POE must be comparable to that of BOE.

Even though these predictions are formulated intentionally in rather broad terms, their verification for specific ASSBs can be extremely difficult. Indeed, the accumulation of a detailed data set with fine angular resolution and phase-angle coverage extending down to a small fraction of a degree typically takes several observation cycles separated by long periods (often lasting for years if not decades!) during which the corresponding sun–object–observer configurations are unsuitable. Furthermore, the photometric and polarimetric accuracy and precision of the instruments used must be very high.

Despite the above-mentioned challenges, the accumulated body of high-quality longterm astronomical observations, including the most recent results by the second and third authors of this paper, does allow one to identify, for the first time, a representative class of high-albedo ASSBs with unique opposition properties. This class includes the so-called E-type asteroids 44 Nysa and 64 Angelina, the planetary satellites Io, Europa, Ganymede, and Iapetus, and the A and B rings of Saturn. The results of photometric and polarimetric observations of these objects in the visible spectral range are summarized in Fig. 3 and reveal the following striking features.

1. Each photometric phase curve has a linear background with a superposed nonlinear peak centered at opposition. The backscattering intensity peaks are extremely narrow. Their actual angular widths are still uncertain because (i) the data points remain sparse, especially for Io, Ganymede, and Iapetus; (ii) the smallest phase angle in the actual astronomical observations is never equal to zero; and (iii) the Sun is a source of light with a nonzero angular width when viewed from an ASSB. However, it is obvious that the peaks are much narrower than those caused by shadow hiding in dark regoliths of low-albedo ASSBs such as the Moon.<sup>15</sup>
2. Each polarization phase curve in Fig. 3 exhibits a narrow local minimum centered at a phase angle approximately equal to the angular width of the corresponding intensity peak. Each minimum is superposed on a much broader, nearly parabolic negative polarization branch outlined schematically by a solid curve.<sup>38</sup>

The angular widths of the backscattering intensity peaks in Fig. 3 are consistent with the results of theoretical computations of CB<sup>17</sup> for particle sizes of the order of the wavelength, packing densities ranging from several percent to approximately 40%, and particle compositions ranging from water ice (Europa, Saturn's rings) to silicates (44 Nysa and 64 Angelina). The amplitudes of the peaks are also consistent with

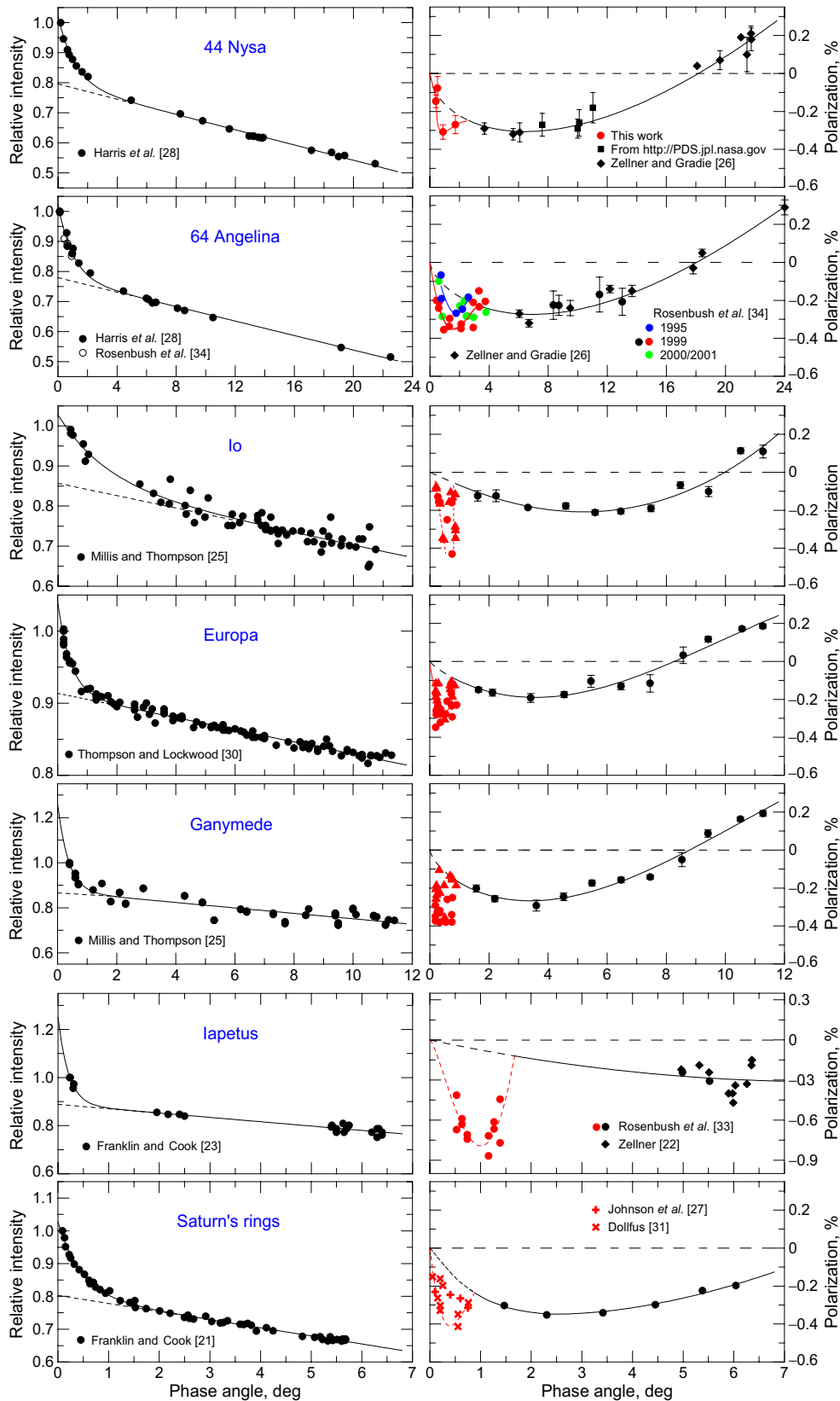


Fig. 3. Relative intensity and linear polarization versus phase angle for high-albedo ASSBs. The intensity is normalized to unity at the smallest phase angle available. The plane through the Sun, the object, and the observer serves as the reference plane for defining the Stokes parameters. The polarization data for Io, Europa, Ganymede, and Saturn's rings at phase angles greater than 1° were obtained by averaging data from Refs. 24, 27, 29, 32, and 35 over 1° intervals with equal weight assigned to each observation. The intensity data were fitted with an exponential-linear function.<sup>36</sup> The polarimetric data were fitted by a trigonometric polynomial.<sup>37</sup>

the theory of CB<sup>7,18</sup> and the assumption that a significant fraction of the surface of these ASSBs is covered with a fine-grained material causing CB.

The shapes of the narrow backscattering polarization minima are quite similar to that of POE caused by coherent backscattering from a half-space of nonabsorbing Rayleigh scatterers (Fig. 2). The magnitudes of the polarization minima are smaller than that in Fig. 2 and are different for the different ASSBs. This is not surprising since the actual regolith grains are not Rayleigh scatterers, and their sizes and refractive indices cannot be expected to be the same for all the ASSBs. Furthermore, the fraction of the visible surface causing CB can also vary with object, thereby changing the resulting polarization.

### 3. Conclusion

A more quantitative analysis of these observational data in terms of specific physical parameters is hardly possible at this time given the limited nature of the dataset, the constrained theoretical ability to compute all radiometric and polarimetric characteristics of CB for realistic polydisperse particle models,<sup>20,42</sup> and the extreme morphological complexity and heterogeneity of the surfaces of the ASSBs. It is fundamentally important, however, that the observations exhibit both BOE and POE and are in a reasonable quantitative agreement with the existing theory. Furthermore, no other optical mechanism is currently known to produce simultaneously both opposition features with their unique morphological characteristics. Therefore, the data summarized in Fig. 3 do appear to represent a critical mass of evidence that, however artificial and subtle the effect of CB may seem to be, it can still occur in a purely natural, majestic, and virtually timeless context of the solar system. This conclusion is the main result of our analysis.

We must conclude this paper with a word of caution. It should be recognized that the introduction of the very concepts of ladder and maximally crossed diagrams and the very definition of CB as the result of summing all cyclical diagrams<sup>1–5</sup> implies that each particle in a particulate layer is located in the far-field zones of all the other particles.<sup>7</sup> This far-field assumption is likely to be violated in the case of many regolith surfaces of ASSBs, which makes the interpretation of astronomical observations far less straightforward than that of laboratory measurements for dilute particle suspensions. However, our limited objective was not to obtain precise numerical fits to the observations. This would have been impossible anyway, since the regolith surfaces are expected to be highly heterogeneous and exhibit numerous drastic variations of morphology and composition within essentially any telescopic field of view. We believe, therefore, that our semiquantitative analysis of the astronomical observations based on the existing theory of CB is justified, especially in view of the fact that the observations exhibit a unique combination of BOE and POE and do not appear to contradict any relevant theoretical prediction.

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